FINAL
IN-77-CR
8442
9P

NASA CONTRACTOR REPORT

NASA-CR-195821

ARC-HEATER PERFORMANCE RESEARCH

Charles E. Shepard
Prabha Durgapal

Eloret Institute
3788 Fabian Way
Palo Alto, CA 94303

Prepared for

Ames Research Center
under Cooperative Agreement NCC2-688

NASA
National Aeronautics and Space Administration

Ames Research Center
Moffett Field, California 94035

(NASA-CR-195821) ARC-HEATER PERFORMANCE RESEARCH Final Technical Report, 1 Apr. 1990 - 31 Jan. 1994 (Eloret Corp.) 9 p

N94-32774

Unclas

G3/77 0008442

NASA CONTRACTOR REPORT

ARC-HEATER PERFORMANCE RESEARCH

Charles E. Shepard
Prabha Durgapal

CONTRACT NAS2–

NASA

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle	5. Report Date
ARC-HEATER PERFORMANCE RESEARCH	29 April 1994
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Charles E. Shepard and Prabha Durgapal	
	10. Work Unit No.
9. Performing Organization Name and Address Eloret Institute 3788 Fabian Way Palo Alto, CA 94303	11. Contract or Grant No. NCC2-688
	13. Type of Report and Period Covered 4/1/90 to 1/31/94
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration, Washington, D.C., 20456	14. Sponsoring Agency Code

15. Supplementary Notes

Point of Contact: Charles E. Shepard and Prabha Durgapal
c/o 229-4 NASA Ames Research Center, Moffett Field, CA 94035

16. Abstract

The tasks performed can be divided into the following categories:

1. An analysis of the electric arc phenomena, especially near the electrodes.
2. A parametric study of arc-jet performance by means of a computer code (ARCFLO) and verification with experimental data where possible.
3. The development of a data acquisition system to collect the above experimental data using Ames arc-jets.
4. A study of the critical components (electrodes and constrictor disks) and suggestions of how to improve their performance. The investigators have been successful in completing these tasks as described below.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
arc-heater constrictor disks arc-jet radiative heat flux computation	unclassified, unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
unclassified	unclassified		

*For sale by the National Technical Information Service, Springfield, Virginia 22161

ARC-HEATER PERFORMANCE RESEARCH

Final Technical Report

for
Cooperative Agreement NCC2-688

for the period

April 1, 1990 - January 31, 1994

Submitted to

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035

Thermosciences Division, James O. Arnold, Chief

Thermophysics Facilities Branch
Joseph Hartman, Chief and Technical Officer

Prepared by

ELORET INSTITUTE
3788 Fabian Way
Palo Alto, CA 94303
Phone: 415 493-4710
Telefax: 415 424-9876

K. Heinemann, President and Grant Administrator
Charles E. Shepard, Principal Investigator
Prabha Durgapal, Co-Principal Investigator

29 April, 1994

This final report for NASA-Ames/Eloret Institute Cooperative Agreement NCC2-688 is being submitted in two parts. Part A describes work performed by Principal Investigator **Charles E. Shepard** and Research Assistants **Thinh M. Ha** and **Jaswinder S. Taunk**, and Part B focuses on work by Co-Principal Investigator, **Dr. Prabha Durgapal**.

Part A

Abstract

The tasks performed can be divided into the following categories:

1. An analysis of the electric arc phenomena, especially near the electrodes.
2. A parametric study of arc-jet performance by means of a computer code (ARCFLO) and verification with experimental data where possible.
3. The development of a data acquisition system to collect the above experimental data using Ames arc-jets.
4. A study of the critical components (electrodes and constrictor disks) and suggestions of how to improve their performance. The investigators have been successful in completing these tasks as described below.

Description of Completed Work

The long-term goal of the Ames Arc Jet Research Group has been the development of a "next generation" arc jet capable of higher performance (stagnation enthalpy and/or higher pressure) with a much higher net stream power input. Although the final arc-jet configuration will depend on the enthalpy - pressure level that is chosen, many problems that are common to any configuration have been studied. These include the following:

1. The successful design, acquisition, and test of a data acquisition system suitable for arc-jet research. This system is described in "Analytical and Experimental Analysis of an Electric Arc Jet"[5] by Jaswinder Singh Taunk.

2. Arc-Jet performance calculations utilizing the NASA/Ames ARC-FLO computer code (see ref. (1)).

3. The correlation of the above calculations in terms of arc-jet operating parameters. An example is "A Sonic Flow Equation for Electric Arc Jets[6] by Charles Shepard and Jaswinder Taunk of Eloret and Frank Milos of NASA/Ames.

4. In the course of the above correlation, it was found that the swirl (given to the air that is injected along the constrictor column) has an effect on the sonic flow relationship. This effect is quite large (approx. 30 %) for cold-air flow[7].

5. An analytic study of the critical downstream multiple electrode (cathode) region. Results of these studies by Prabha Durgapal are presented in Part B of this report.

6. A preliminary study of the arc column radiation and heat flux was made. The results of this study are reported in a paper in preparation entitled "Spectral Measurements in the Arc Column of an Arc-Jet Wind Tunnel"[8] by Imelda Terrazas-Salinas, Chul Park, Tony Strawa of NASA-Ames and Nigel Gopaul of Eloret Institute. This paper will be presented at the AIAA Aerospace and Testing Conference at Colorado Springs, CO, June 1994.

7. The above experiment required the design and construction of a special "window" in the arc-jet constrictor. This water-cooled copper disk is described in a proposed paper entitled "Design and Verification of a Copper Disk for Radiation Measurements in the constrictor Region of an Arc Jet"[9] by Jaswinder Taunk and Charles Shepard of Eloret Institute and Armando Carrasco of NASA-Ames. This paper will be presented at the 40th International Instrumentation Symposium in Baltimore, MD, May 1994.

8. The problem of obtaining equal division of the arc-current for multiple-electrodes was studied. The results were reported in a memo to Mr. Jerry Mitvalsky of NASA-Ames[10]. A series of experiments with the Ames Panel Test Facility Arc Jet confirmed the finding that the upstream electrode that is furthest from the constrictor is most sensitive to changes in operating conditions. It was found that the set of ballast resistors must have a relatively high resistance (greater than about 0.5 Ohm) if good current balancing is to be maintained.

9. The next-generation arc-jet (capable of much higher power input and higher performance) will require better water-cooling of the constrictor disks. The present Maecker cooling design uses a the centripetal force induced by the cusped cooling water geometry to sweep away and collapse the steam bubbles and thereby avoid burn-out. Previous heat-conduction analyses indicate that the present working limit of 10 kw/cm^2 can be increased to about 20 kw/cm^2. A new 3-dimensional polar coordinate Fortran computer code is being developed to permit more accurate heat flux calculation by including the effect of a finite constrictor disk thickness.

10. The most critical problem is the improvement of the electrodes that will permit stable operation at much higher arc current limits. If the pressure is kept below 10 atmospheres, a tungsten cathode could be used. This would be a much simpler electrode. If the incandescent tungsten were shielded by argon, a single tungsten rod could carry as much current as the PTF four-electrode package. Multiple rods could carry the required total current of future arc jets and would be much cheaper and easier to maintain. A small single tungsten rod and water cooled anode has been set up in Bldg. 238. A brief discussion of alternative electrodes is included in short paper presented at the October 7, 1992 Arc Jet Research Meeting.[11] Multiple element copper anodes are an alternative electrode as suggested in an AIAA paper, "Thermal Analysis of an Arc Heater Electrode with a Rotating Arc Foot" by F.S. Milos and C.E. Shepard.[12]

PART B

Abstract

A theoretical model of the electrode phenomena, leading to the computation of the current density distributions, arc spot temperature, spot size, sheath voltage, ablation velocity, ablation rate and arcfoot rotation frequency, is put forward. Computations for an atmospheric arc, at load currents ranging from 800 to 3000 amp, in 1) one segment and 2) 4 segment electrode configurations, are conducted[1] . In another paper computations are performed for operating pressures in the range 50-200 atm and load currents in the range 6000-18000 amps[2]. At high pressures spot size remains reasonably small, even for high load currents. Smaller spot size may allow us to design thinner electrodes. However higher load currents lead to high spot temperatures and this can cause ablation of the electrode material. In order to reduce material ablation at very high currents and prolong electrode life, the operating pressure must be high and the arc should be rotated.

Radiation and Joule heating in the electrode region of an arc heater are discussed. Radiative transport equations for a true axisymmetric geometry are used. An expression for the divergence of radiative heat flux is computed analytically[3]. A subsonic code is developed to numerically solve the fluid equations with strongly coupled radiation and Joule heating, representative of a high pressure and high current arc heater[4]. The Joule heating term is computed using the electromagnetic code. The equilibrium gas model consists of seven species. The fluxes are differenced using Van Leer flux splitting. Using this code the effects of radiative cooling on the thermodynamic parameters of the arc core are discussed.

Objective

The purpose of this work is to study the operation and design of the ring electrodes used in segmented arc-heaters. The overall objectives of this study are:
(1) to develop a physical understanding of the behavior and dynamics of the arc near an electrode, and of the arcfoot on the surface of an electrode, in a segmented arc heater;
(2) to develop the computational capability to simulate and predict the arc behavior on the surface and in the vicinity of an electrode; and
(3) to develop engineering design criteria that will assist in the design of efficient and long-life electrodes. The results of this study will provide the basis for improved electrode designs that will support higher power operation.

Description of the problem

Ames Research Center is currently operating a variety of arc-heater facilities. In an arc heater, as the name suggests, the gas is heated by means of an electric arc. Of interest here is the segmented arc heater. The main components of a typical facility include a constricted arc heater, several interchangeable Mach number nozzles, a walk-in test chamber, and ancillary subsystems consisting of a steam-ejector vacuum system, cooling water system and automated data acquisition system. The two electrodes are located on either side of the constrictor. The anode forms the upstream electrode and the cathode forms the downstream electrode. An electrode package consists of multiple rings that are the actual electrodes and each active electrode ring is insulated from the others by insulator rings and is individually ballasted. Each ring electrode has a given current rating. Electrodes are added to the stock until the number of electrode rings can handle the total current expected in the arc column. With proper adjustment of the individual ballasts the electrode rings can be made to share current more or less equally. For the purpose of this study it is assumed that future high pressure and high enthalpy arc jets will have similar configurations with variations in electrode number and size.

An electric arc is a discharge of electricity between electrodes in a gas or vapour, with characteristic cathode or anode voltage drop at the electrodes. An arc at atmospheric pressure and above is characterised by a small intensely brilliant core surrounded by a comparatively cooler region of flaming gases. The core is at such high temperatures that all gases are completely dissociated. The current density at the cathode of an arc is very large and is practically independent of the arc current. It depends only on the material of the cathode, specially on its thermionic emission characteristics. The electrode material most commonly used is copper or copper alloy with high thermal conductivity to assure an adequate heat transfer rate capability.

Due to the high temperature of the arc spot, the electrode material at that location melts or sometimes instantneously vaporizes releasing electrode material and contaminating the flowing gas. Methods to reduce contamination from electric arc include:
(1) arcfoot rotation by vortex generation or magnetic field interaction.
(2) selecting electrode material that can attain high levels of thermionic emission at relatively lower spot temperatures.
(3) selecting electrode material with high melting point.

The primary limitations to the design of an arc heater, in excess of 60 MW power, have been 1) arc control, 2) downstream electrode (cathode) erosion,and 3) radiation loss. As NASA embarks on the design of a 300 MW heater, it is imperative that these phenomena are well understood and brought under control. In two papers[1-2] the electrical characteristics in the downstream electrode region (cathode) of an arcjet were

investigated at high temperatures and high pressures. At high temperatures radiative energy transfer becomes an important mode of heat transfer together with conduction and convection. For these conditions the energy equation of the flowfield must include the Joule heating term, together with the radiation term. The final code developed using the present work will be validated against data obtained from existing arc jets and will later be used for developing and designing future high pressure, high current arc jets.

Technical Approach and Accomplishments

The physical model of the various processes occuring in an arc heater is being developed in a step by step procedure. These steps are:

A. Electrical characteristics in the downstream cathode region of the arc jet: The stream function formulation of the current density in the axisymmetric flow field of the downstream cathode region, based on Maxwell's equations for given thermal properties, are derived[1-2]. These equations together with the necessary boundary and subsidiary conditions for the electrode region are solved using Gauss-Seidel successive relaxation technique. The results of this analysis provide the current density distribution in the downstream cathode region. It also provides the electric field at the location where the arcfoot terminates. A simple heat transfer model was also developed for use with this code[1-2]. Thermal properties of the region under consideration are determined using this model.

B. Arcfoot parameters: A model was developed to compute arcfoot parameters[1-2]. These include arcfoot spot size, spot temperature, cathode voltage drop, ablation velocity, rate of material loss when the spot temperature is greater than the melting point of the electrode material, and arcfoot rotation frequency. These are determined by analysing the ionization and thermionic emission processes in the electrode region. Arcfoot rotation frequency is determined by balancing the magnetic force against the aerodynamic drag. Arcfoot rotation frequency is compared with recently acquired experimental data. Results are provided for an atmospheric arc with load current in the range 800 to 3000 A in Ref. 1, and for high pressure (50-200 atm) and high current (6000-18000 A) arcs in Ref. 2.

C. Radiative Heat transfer: An expression for the divergence of the radiative heat flux is computed analytically in axisymmetric geometry[3]. The radiation term is strongly coupled[4]. For this the Jacobians with respect to the species density and temperature are needed. The derivative of the divergence of radiative heat flux with respect to the density was also computed analytically. In reference 3, the expression for the radiative heat flux is rendered analytically differentiable/integrable by using appropriate techniques to remove the singularities. This makes it possible to obtain the expression for the divergence of radiative heat flux analytically. This leads to considerable reduction in computation time.

D. Joule Heating: At high temperatures radiative energy transfer becomes an important mode of heat transfer together with conduction and convection. For these conditions the enegy equation of the flowfield must include the Joule heating term together with the radiation term. A subsonic code is developed to numerically solve the fluid equations with strongly coupled radiation and Joule heating terms, representative of a high pressure and high current arc heater. The Joule heating term is computed using the previously developed electromagnetic code[1-2]. The equilibrium gas model consists of seven species. The fluxes are differenced using Van Leer flux splitting. Using this code[4] the effects of radiative cooling on the thermodynamic parameters of the arc core are discussed.

PUBLICATIONS and PRESENTATIONS

1. Prabha Durgapal, *"Current Distribution in the cathode Area of an Arc Heater,"* AIAA Journal of Thermophysics and Heat Transfer, **7**, 241, 1993; also AIAA-Paper 91-1385, 1991.

2. Prabha Durgapal, *"Electrode Phenomena in High Cu rrent, High Pressure Arc Heaters,"* AIAA Journal of Thermophysics and Heat Transfer, **7**, 412, 1993; also AIAA-Paper 92-0810, 1992.

3. Prabha Durgapal, *Radiative Transfer in the Electrode Region of an Arc Heater,"* AIAA-Paper 92-2872; presented at the 27th Thermophysics Conference, Nashville, TN, 1992.

4. Prabha Durgapal and G.E. Palmer, *Strongly Coupled Radiative Transfer and Joule Heating in the Electrode Region of an Arc Jet,"* AIAA-Paper 93-2801; presented at the 28th Thermophysics Conference, Orlando, 1993.

5. Jaswinder S. Taunk,*"Analytical and Experimental Analysis of an Electric Arc Jet,"* MS Project Report, San Jose State University.

6. Charles E. Shepard, Frank S. Milos, and Jaswinder S. Taunk,*"A Sonic Flow Equation for Electric Arc Jets,"* AIAA-Paper 93-3183.

7. Charles E. Shepard, Internal memorandum to John Balboni, NASA-Ames, Oct.6,1993.

8. Imelda Terrazas-Salinas, Chul Park, and Tony Strawa, *"Spectral Measurements in the Arc Column of an Arc Jet Wind Tunnel,"* AIAA paper, Colorado Springs, 1994, in preparation.

9. Jaswinder S. Taunk, Charles E. Shepard, and Armando Carrasco, *"Design and Verification of a Copper Disk for Radiation Measurements in the Constrictor Region of an Arc Jet,"* 40th International Instrumentation Symposium, Baltimore, MD, 1994, in preparation.

10. Charles E. Shepard, Internal Memorandum to Jerry Mitvalsky and Wayne Harry, NASA-Ames, Nov. 12,1993.

11. Charles E. Shepard, *"New Electrodes for Arc Jets,"* Internal paper for ArcJet Research Group, Oct. 7, 1992.

12. Frank S.Milos and Charles E. Shepard,*"Thermal Analysis of an Arc Heater Electrode with a Rotating Foot,"* AIAA-Paper 93-2855, Orlando, FL 1993.